

AD-A261 685



DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

2

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
FINAL/01 JAN 90 TO 30 SEP 924. TITLE AND SUBTITLE
MULTIVARIABLE CONTROL FOR
FLEXIBLE IC PROCESSING (U)

5. FUNDING NUMBERS

6. AUTHOR(S)

Professor Thomas Kailath

DTIC
ELECTE
MAR 5 19937149/01/DARPA
F49620-90-C-0014

7. PERFORMING ORGANIZATION NAME(S)

Stanford University
Electrical Engineering
Stanford, CA 94305-41258. PERFORMING ORGANIZATION
REPORT NUMBER

AFOSR-TR- 93 0108

9. SPONSORING, MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/NM
110 DUNCAN AVE, SUTE B115
BOLLING AFB DC 20332-000110. SPONSORING, MONITORING
AGENCY REPORT NUMBER

F49620-90-C-0014

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION IS UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The objective of this DARPA research project was to develop real-time control systems using in-situ sensors for semiconductor manufacturing. Our initial application was the development of a temperature control system for Rapid Thermal Processing (RTP) equipment. We developed mathematical models of RTP, analyzed them, identified and validated these models, deduced several control algorithms and finally applied them to real systems at Stanford University and at Texas Instruments. Also, based on our analysis, we modified the design of the system hardware (lamp array) and also proposed an optimal lamp array design technique.

93 3 4 042

93-04670



14. SUBJECT TERMS

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

15. NUMBER OF PAGES

16. PRICE CODE
SAR (SAME AS REPORT)17. SECURITY CLASSIFICATION
OF REPORT18. SECURITY CLASSIFICATION
OF THIS PAGE19. SECURITY CLASSIFICATION
OF ABSTRACT

20. LIMITATION OF ABSTRACT

INFORMATION SYSTEMS LABORATORY

DEPARTMENT OF ELECTRICAL ENGINEERING
STANFORD UNIVERSITY · STANFORD, CA 94305



Multivariable Control for Flexible IC Processing

Thomas Kailath, Principal Investigator
Information Systems Laboratory
Department of Electrical Engineering
Stanford University, Stanford, CA 94305-4055

November 30, 1992

Final Annual Report: October 1, 1991 – September 30, 1992

Sponsored by:
Defense Advanced Research Projects Agency
DARPA Order No. 7149
Monitored by AFOSR under Contract F49620-90-C-0014

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Defense Advanced Research Projects Agency of the U.S. Government.

Contents

Project Personnel	3
Executive Summary	4
List of Publications	10
Ph.D. Thesis Abstracts	16
List of Presentations	19

DHC QUALITY INSPECTED 1

Accession For	
NTIS CRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and/or Special
A-1	

Project Personnel

(10/1/90 – 9/30/92)

Principal Investigators

Professor Thomas Kailath
Professor Stephen Boyd
Professor Gene Franklin
Professor Krishna Saraswat

Research Associates

Dr. Charles Schaper
Dr. A. Paulraj

Research Assistants

Hamid Aghajan
V. Balakrishnan (Ph.D. September 1992)
Chih-Yuan Chang
Young Man Cho
Babak Hassibi
Gerard Hoffmann (Ph.D. December 1992)
Babak Khalaj
Stephen Norman (Ph.D. July 1992)
Poogyeon Park
Yaoting Wang

Computer Programmers

Marc Goldberg
Michael Grant

Administrative Assistants

Barbara McKee
Christine Lincke

Multivariable Control for Flexible IC Processing

DARPA Project, January 1, 1990 – September 30, 1992

Executive Summary
(T. Kailath and C. Schaper)

1 Project Description

The objective of this DARPA research project was to develop real-time control systems using in-situ sensors for semiconductor manufacturing. Our initial application was the development of a temperature control system for Rapid Thermal Processing (RTP) equipment. We developed mathematical models of RTP, analyzed them, identified and validated these models, deduced several control algorithms and finally applied them to real systems at Stanford University and at Texas Instruments. Also, based on our analysis, we modified the design of the system hardware (lamp array) and also proposed an optimal lamp array design technique.

2 Outline of Results

Our approach began by analyzing the performance limits of available RTP equipment using detailed physical models [1]. It was evident from these studies that multivariable actuation (i.e. multiple independently controllable lamps) was needed in order to achieve uniform and slip-free processing.

We then developed modeling strategies to characterize the temperature dynamics in Rapid Thermal Processing (RTP) systems with multiple independently controllable lamps.

Two approaches were investigated in the development of the models. The first method [2] viewed the RTP system as a black-box. A mathematical model of the temperature effects for this representation was determined by exciting the inputs (lamp powers) and measuring the outputs (thermocouples or pyrometer measurements). A dynamic linear model of the system was then determined by correlating the inputs against the outputs. To automatically identify this correlation for RTP systems, a

novel technique was developed and tested. This technique employed signal processing ideas from newly developed high-resolution sensor array processing theory that have the advantage of processing large quantities of data quickly (relative to alternative approaches). In order to handle the nonlinear characteristics of RTP due to radiative heating, multiple linear models were obtained at different operating points. Then, a Linear Quadratic Gaussian (LQG) controller combined with convex optimization techniques was designed for these linear models and successfully applied to the experimental RTP system at Stanford University [3], [4].

The second approach employed a joint mathematical/physics-based approach [5], [6]. In this technique, a physical model of RTP was derived. The model incorporated actuator and sensor dynamics as well as the wafer heating dynamics. Thus, the model captured the nonlinear effects of RTP. However, the physics-based model contained parameters that could not be accurately determined from first principles. Consequently, experimental data was obtained from the RTP equipment by exciting the lamp powers and measuring temperature. This data was then optimally fitted to the parameters in the nonlinear model structure suggested by the physical derivation. We then developed a real-time controller for such models. The controller used a global-model based predictor to track the desired temperature trajectory and a local-model based feedback compensation mechanism to correct for disturbances and modeling errors. This temperature control strategy was successfully applied on a variety of significantly different RTP equipments.

Our control strategy was first verified on the Stanford RTP system which employs a three-zone lamp, three-point thermo-couple (t/c) sensor for four-inch wafers. Next, the control strategy was transferred and applied to the Advanced Vacuum Processors (AVPs) at Texas Instruments (TI) in Dallas for the following equipment configurations: four-zone TI lamps and six-zone G-squared lamps, four-point t/c sensors, six-inch wafers, and a TI chamber/showerhead arrangement. The control system was tested on silicide react, silicide anneal, and tank anneal process cycles. Work is continuing at TI to evaluate the temperature controller on additional processes, to integrate it with noninvasive temperature sensors, and to incorporate it into the CIM environment.

Besides the design of real-time model-based control systems, these models were employed in designing an Extended Kalman Filter to reduce measurement bias and

noise in pyrometry. Our approach is based on reconciling the model behavior and the measurements. This technique has been studied through simulation and promises to improve pyrometric measurements in the presence of emissivity variations. Another byproduct of our modeling studies, is an optimal design of lamp arrays in RTP systems [7]. Experimental validation of this method remains to be done.

Modern control theory also offers other opportunities to greatly improve the quality and reproducibility of semiconductor processes. We addressed the computer software and hardware implementational issues for real-time control of semiconductor equipment and processes, by taking an approach based on the theory of discrete event systems. The main advantage of this theory for manufacturing applications is that multitasking computer programs can be synthesized or updated quickly and reliably when either new recipes are requested or new equipment is added. Our accomplishments to date include a novel multitasking software environment that is developed for manufacturing processes in general and was applied to the Rapid Thermal Multiprocessor (RTM) at Stanford. In addition, the discrete event approach has been developed in a hybridized framework that incorporates real-time dynamic control. This work is one of the first to apply this theory and framework to a manufacturing process [8]. Again, the computer software was successfully transferred to TI.

3 Applications in Lithography

Though the original program only envisaged use of signal processing ideas only in so far as they were appropriate for model identification and control (see [2], [8], [7]), it became clear to us that these ideas could be useful in a much broader range of problems in semiconductor manufacturing. These applications are the major focus of another recently initiated DARPA effort, but some preliminary results may be noted here. We focused our initial investigations in the area of lithography. Here new methods are being developed to improve the capabilities of optical confocal and correlation microscopes to measure the dimensions of features on semiconductor wafers. These measurements can then be used to monitor and eventually control the lithography process. Furthermore, the algorithms are general and have the potential for many applications in machine vision besides lithography including robotic vision [9], [10], [11], [12], [13]. We also investigated image processing techniques for automated de-

fect inspection [14]. In addition, a new computational technique is being developed to systematically design phase-shifting masks for arbitrary integrated circuit geometries. These masks can improve the resolution of photolithography without renovation of current optical exposure systems [15]. Previously, design techniques of phase-shifting masks were heuristic and limited to very simple patterns. Initial designs using the new technique have been developed for the three patterns of most interest: a contact hole, a single space, and periodic lines/spaces [15].

4 Summary

This project has initiated the task of applying the ideas of modern control, optimization, computation and signal processing theories to important areas of semiconductor manufacturing. The results have demonstrated that modern systems point of view can significantly improve current methodologies used in the fabrication of integrated circuits.

Our work suggests the following general comments:

- Real-time control and sensing can be very useful to the semiconductor industry for improving yields and reducing time-to-market. This approach should complement the Statistical Process Control (SPC) concept of run-to-run control.
- Simultaneous coordination of equipment design, control, and sensor technologies is required to achieve this goal.
- Sensing, which is essential to control, is a major problem in the IC industry for several reasons, including noninvasive sensing requirements, submicron features, and processing complexity. Nonetheless, this challenge can be met by using advanced signal processing algorithms, *e.g.*, to reduce the accuracy burden on the sensor itself.
- Consolidation of physics-based and mathematical-based modeling concepts are needed to improve prediction/extrapolation for process control and process synthesis.

- Extension and practical reduction of existing control theory is needed to address specific concerns of the IC manufacturing industry such as reproducibility and uniformity.
- A lot more work can profitably be done along these lines, not just for the semiconductor industry but for advanced materials processing in general.

References

- [1] S.A. Norman, *Wafer Temperature Control in Rapid Thermal Processing*, PhD thesis, Stanford University, 1992.
- [2] Y.M. Cho and T. Kailath, Model Identification in Rapid Thermal Processing Systems, *IEEE Tran. on Semiconductor Manufacturing*, 1992, Accepted for publication.
- [3] P.J. Gyugyi, Y.M. Cho, G. Franklin, and T. Kailath, Control of Wafer Temperature in Rapid Thermal Processing: Part I - State Space Model Identification and Control, *Automatica*, 1992, Submitted.
- [4] P.J. Gyugyi, Y.M. Cho, G. Franklin, and T. Kailath, Control of Wafer Temperature in Rapid Thermal Processing: Part II - Convex Optimization, *Automatica*, 1992, Submitted.
- [5] S.A. Norman, Optimization of Transient Temperature Uniformity in RTP Systems, *IEEE Trans. Electron. Dev.*, **39**(1):205-207, January 1992.
- [6] C.D. Schaper, Y.M. Cho, and T. Kailath, Low-Order Modeling and Dynamic Characterization of Rapid Thermal Processing, *Applied Physics A*, April 1992.
- [7] Y. Cho, A. Paulraj, G. Xu, and T. Kailath, A Contribution to Optimal Lamp Design in Rapid Thermal Processing System, *IEEE Tran. on Semiconductor Manufacturing*, 1992, Submitted.
- [8] S. Balemi, G. Hoffmann, P. Gyugyi, H. Wong-Toi, and G. Franklin, Supervisory Control of a Rapid Thermal Multiprocessor, *Joint Automatica-IEEE Transactions on Automatic Control*, November 1991, Accepted for publication.

- [9] Y.T. Wang, C.D. Schaper, and T. Kailath, Pattern Recognition of Trench Width using a Confocal Microscope, *IEEE Trans. Semiconductor Manufacturing*, 1992, Submitted.
- [10] H.K. Aghajan, C.D. Schaper, and T. Kailath, Pattern Recognition Algorithms for Linewidth Measurement, In *Proc. of SPIE Symp. on Microlithography, IC Metrology, Inspection, and Process Control VI, Vol. 1673*, pp. 83-86, San Jose, CA, 1992.
- [11] H.K. Aghajan and T. Kailath, Sensor Array Processing Techniques for Super Resolution Multi-Line Fitting and Straight Edge Detection, *IEEE Trans. on Image Processing*, to appear in 1993.
- [12] H.K. Aghajan, C.D. Schaper, and T. Kailath, Machine Vision Techniques for Sub-Pixel Estimation of Critical Dimensions, *Optical Engineering*, to appear in 1993.
- [13] H. K. Aghajan and T. Kailath, Sensor Array Processing Techniques for Super Resolution Multi-Line Fitting and Straight Edge Detection, *IEEE Trans. Image Processing*, to appear, 1993.
- [14] B.H. Khalaj, H.K. Aghajan, and T. Kailath, Automated Direct Patterned Wafer Inspection, In *IEEE Workshop on Applications of Computer Vision*, Palm Springs, CA, to appear November 1992.
- [15] C.Y. Chang, C.D. Schaper, and T. Kailath, Computer-aided Optimal Design of Phase-shifting Masks, In *Proceedings of SPIE symposium on Microlithography, Conference 1674, Optical/Laser Microlithography V*, San Jose, CA, 1992.

Publication List

Multivariable Control for Flexible IC Processing January 1, 1990 – September 30, 1992

Published Journal Papers

- [1] Stephen A. Norman, Optimization of transient temperature uniformity in RTP systems, *IEEE Trans. Electron Dev.*, **39**(1):205–207, January 1992.
- [2] Charles D. Schaper, Young Man Cho and Thomas Kailath, Low-Order Modeling and Dynamic Characterization of Rapid Thermal Processing, *Applied Physics A.*, April 1992.

Papers Accepted for Publication

- [1] H. K. Aghajan and T. Kailath, Sensor Array Processing Techniques for Super Resolution Multi-Line Fitting and Straight Edge Detection, *IEEE Trans. on Image Processing*, to appear, 93.
- [2] H. K. Aghajan, C. D. Schaper, and T. Kailath, "Machine Vision Techniques for Sub-Pixel Estimation of Critical Dimensions", *Optical Engineering*, to appear, 93.
- [3] Young Man Cho, and Thomas Kailath, Model Identification in Rapid Thermal Processing System. Accepted to IEEE Transactions on Semiconductor Manufacturing, 1992.
- [4] H. Wong-Toi and G. Hoffmann, The Control of Dense Real-Time Discrete Event Systems, Technical Report STAN-CS-92-1411, Dept. of Computer Science, Stanford University, CA, March 1992 accepted for publication in IEEE Transactions on Automatic Control
- [5] S. Balemi, G.J. Hoffmann, P. Gyugyi, H. Wong-Toi, and G.F. Franklin, Supervisory control of a rapid thermal multiprocessor, Technical report ISL-GFF-91-1, Information Systems Laboratory, Stanford University, CA 94305, November 1991, accepted for publication in Joint

Automatica—IEEE Transactions on Automatic Control 1993 issue, also presented at a workshop on discrete event systems (DES) in Amherst, MA, June 1991.

Papers Under Review

- [1] Young Man Cho, Guanghan Xu and Thomas Kailath, Fast Identification of State-Space Models via Exploitation of Displacement Structures. Submitted to IEEE Transactions on Automatic Control, 1992.
- [2] Young Man Cho, Guanghan Xu and Thomas Kailath, Fast Recursive Identification of State Space Models Via Exploitation of Displacement Structure. Submitted to Automatica, 1992.
- [3] Y. Cho, A. Paulraj, G. Xu and T. Kailath, A Contribution to Optimal Lamp Design in Rapid Thermal Processing System. Submitted to IEEE Transactions on Semiconductor Manufacturing, 1992.
- [4] Paul J. Gyugyi, Young Man Cho, Gene Franklin, and Thomas Kailath, Control of wafer temperature in rapid thermal processing: Part I - state space model identification and control, *Automatica*, 1992, Submitted.
- [5] Paul J. Gyugyi, Young Man Cho, Gene Franklin, and Thomas Kailath, Control of wafer temperature in rapid thermal processing: Part II - convex optimization, *Automatica*, 1992, Submitted.
- [6] Stephen A. Norman, Optimal multivariable control of wafer temperature in RTP systems, *IEEE Transactions on Semiconductor Manufacturing*, November 1991, Submitted.
- [7] Y-T. Wang, C.D. Schaper, and T. Kailath, Pattern recognition of trench width using a confocal microscope, *IEEE Trans. on Semiconductor Manufacturing*.

Conference Papers

- [1] Hamid K. Aghajan, Charles D. Schaper, and Thomas Kailath,
Edge detection for optical image metrology using unsupervised neural
network learning, In *Proceedings of IEEE Workshop on Neural Networks
for Signal Processing*, Princeton, NJ, 1991.
- [2] H. K. Aghajan and T. Kailath,
"A Subspace Fitting Approach to Super Resolution Multi-Line Fitting
and Straight Edge Detection", In *Proc. of IEEE ICASSP*, pages III:121-
124, San Fransisco, CA, 1992.
- [3] H. K. Aghajan, C. D. Schaper, and T. Kailath,
"Pattern Recognition Algorithms for Linewidth Measurement", In *Proc.
of SPIE Symp. on Microlithography, IC Metrology, Inspection, and Pro-
cess Control VI, Vol. 1673*, pages 83-96, San Jose, CA, 1992.
- [4] H. K. Aghajan, B. H. Khalaj, and T. Kailath,
"Estimation of Skew Angle in Text Image Analysis by Sensor Array
Processing Techniques", In *Proc. of IS&T/SPIE Symp. on Electronic
Imaging Science & Technology*, San Jose, CA, to appear, Jan. 93.
- [5] H. K. Aghajan and T. Kailath,
"SLIDE: Subspace-based Line Detection", In *Proc. of IEEE ICASSP*,
Minneapolis, MN, to appear, April 93.
- [6] Chih-Yuan Chang, Charles D. Schaper, and Thomas Kailath,
Computer-aided optimal design of phase-shifting masks, In *Proceed-
ings of SPIE symposium on Microlithography, Conference 1674, Opti-
cal/Laser Microlithography V*, San Jose, CA, 1992.
- [7] Chih-Yuan Chang, Geraint Owen, Fabian R. Pease, and Thomas
Kailath,
A computational method for the correction of proximity effect in
electron-beam lithography, In *Proceedings of SPIE symposium on Mi-
crolithography, Conference 1671, Electron-Beam, X-Ray, and Ion-Beam
Submicrometer Lithographies for Manufacturing II*, San Jose, CA, 1992.

- [8] Y.M. Cho, C.D. Schaper, and T. Kailath, In Situ Temperature Estimation in Rapid Thermal Processing Systems using Extended Kalman Filtering, In *Material Research Society Proceeding*, Material Research Society, 1991.
- [9] Y. Cho, G. Xu, T. Kailath, and R. Roy, On-Line Identification of State-Space Models via Exploitation of Displacement Structure, pages 141-146, Seoul, Korea, August 1992. 2nd IFAC Algorithms and Architectures for Real-Time Control.
- [10] Y. Cho, A. Paulraj, G. Xu and T. Kailath.
A Contribution to Optimal Lamp Design in Rapid Thermal Processing. In SPIE proceeding, San Jose, CA, September, 1992.
- [11] Young Man Cho, Guanghan Xu and Thomas Kailath.
Fast Identification of State-Space Models via Exploitation of Displacement Structures. In CDC proceeding, Tucson, AZ, December, 1992.
- [12] Young Man Cho, Guanghan Xu and Thomas Kailath.
State-Space Identification via Exploitation of Displacement Structures: Batch and Recursive Processing. In *Proc. of the 26th Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, Nov. 1992.
- [13] Paul J. Gyugyi, Young Man Cho, Gene Franklin, Thomas Kailath, and Richard H. Roy,
Model-based control of rapid thermal processing systems, In *The 1st IEEE Conference on Control Applications*, Dayton, Ohio, September 1992.
- [14] Paul J. Gyugyi, Young Man Cho, Gene Franklin, and Thomas Kailath,
Control of rapid thermal processing: A system theoretic approach, In *Proc. of IFAC World Congress*, 1993, Submitted.
- [15] H. Wong-Toi and G. Hoffmann,
The control of dense real-time discrete event systems, In *Proc. of 30th Conf. Decision and Control*, December 1991.
- [16] G. Hoffmann and H. Wong-Toi,
Symbolic synthesis of supervisory controllers, In *Proc. of American Control Conference*, 1992.

- [17] H. Wong-Toi and G. Hoffmann,
Symbolic supervisory synthesis for the Animal Maze, *Workshop on Discrete Event Systems*, Prague, 1992.
- [18] G. Hoffmann and H. Wong-Toi,
The Input-Output Control of Real-Time Discrete-Event Systems, *13th IEEE Real-Time Systems Symposium*, Phoenix, AZ, December 2-4, 1992.
- [19] B. H. Khalaj, H. K. Aghajan, and T. Kailath,
"Automated Direct Patterned Wafer Inspection", In *IEEE Workshop on Applications of Computer Vision*, Palm Springs, CA, to appear, Nov. 92.
- [20] B. H. Khalaj, H. K. Aghajan, and T. Kailath,
"Automated Direct Patterned Wafer Inspection", In *Proc. of IS&T/SPIE Symp. on Electronic Imaging Science & Technology*, San Jose, CA, to appear, Jan. 93.
- [21] B. H. Khalaj, H. K. Aghajan, and T. Kailath,
"Digital Image Processing Techniques for Patterned Wafer Inspection", In *Proc. of SPIE Symp. on Microlithography, IC Metrology, Inspection, and Process Control VII, Vol.*, San Jose, CA, Submitted, Aug. 92.
- [22] S.A. Norman, C.D. Schaper, and S.P. Boyd, Improvement of Temperature Uniformity in Rapid Thermal Processing Systems using Multivariable Control, In *Materials Research Society Proc.*, Volume 224, Materials Research Society, 1991.
- [23] Stephen A. Norman and Stephen P. Boyd,
Multivariable feedback control of semiconductor wafer temperature, In *Proceedings of American Control Conference*, Chicago, IL, June 1992.
- [24] P. Park, C. D. Schaper, and T. Kailath,
Control strategy for temperature tracking in rapid thermal processing of semiconductor wafers, In *31st Conference on Decision and Control*, Tucson, Arizona, 1992.

- [25] C. Schaper, Y. Cho, P. Park, S. Norman, P. Gyugyi, G. Hoffmann, S. Balemi, S. Boyd, Dynamics and Control of Rapid Thermal Multiprocessor, In *SPIE Conference on Rapid Thermal and Integrated Processing*, September 1991.
- [26] C. Schaper and T. Kailath,
Applications of Control, Computation, and Signal Processing, to Semiconductor Manufacturing, In SPIE proceeding, San Jose, CA, September, 1992.
- [27] C. Schaper, P. Park and T. Kailath
Control of Temperature Uniformity for a 3-Zone Lamp, 3-Point Sensor RTP System, In SPIE proceeding, San Jose, CA, September, 1992.
- [28] C. Schaper, Y. Cho, P. Park, S. Norman, P. Gyugyi, G. Hoffman, S. Balemi, S. Boyd, G. Franklin, T. Kailath, and K. Saraswat, Modeling and control of rapid thermal processing, San Jose, CA, Sept. 1991. SPIE Vol. 1595 Rapid Thermal Processing.

Ph.D. Thesis Abstracts

January 1, 1990 – September 30, 1992

S.A. Norman: Wafer Temperature Control in Rapid Thermal Processing

Abstract: Rapid thermal processing (RTP) is a term used for a number of proposed thermal processes in the manufacture of integrated circuits. In RTP wafers are processed quickly, one at a time in a small oven; the heat source is visible and/or infrared radiation from a lamp array. RTP has process-related and economic advantages over conventional batch thermal processing in tube furnaces. During thermal processing of semiconductor wafers it is essential that the wafer temperature closely follows a pre-specified temperature trajectory and that the temperature profile across the wafer is nearly uniform whenever the wafer is at high temperatures. Ensuring adequate wafer temperature control is more difficult for RTP systems than for conventional batch thermal processing systems. Without adequate wafer temperature control, RTP can not be used in mainstream integrated circuit fabrication.

This thesis considers the problem of controlling axisymmetric RTP systems with multiple independently-controllable lamps. In such systems the relative lamp power settings can be adjusted so that the lamps provide a range of distributions of power over the wafer; this is useful because the ideal distribution of incident energy varies according to processing conditions and changes substantially during a single process cycle.

In the thesis numerical techniques are developed for using a thermal model of RTP to optimize performance of axisymmetric RTP temperature control configurations. In particular, techniques are introduced for minimizing temperature error across the wafer during steady-state hold, minimizing temperature error across the wafer during trajectory-following, and determining optimal rejection of static disturbances with a linear feedback error controller and a fixed sensor configuration. These techniques are based on convex optimization, which means that solutions reached by optimization algorithms are guaranteed to be globally optimal and can be used to determine limits of system performance.

The optimization techniques are used in studies using detailed models of hypothetical RTP systems. The results of the studies support important conclusions: that multi-actuator control is capable of providing much better temperature uniformity than single-actuator control and that limits-of-performance analysis is valuable because optimal performance is sensitive to changes in lamp and sensor configurations.

G. Hoffmann: Discrete Event System Theory Applied To Manufacturing

Abstract: High sophistication and sensitivity to changes in a manufacturing system can only be achieved by a complex scheduling and real-time control system. The high complexity of a real-time control system renders it very prone to programming errors. A minor change in the precise timing or scheduling of interactions between parallel components leads to radically different behaviors. Because of a lack of appropriate real-time multitasking software design tools it is difficult to develop reliable multitasking control systems.

The proposed solution is to model and analyze a complex system in the supervisory control framework introduced by Ramadge and Wonham. The possible executions of the system to be controlled and its processing specification are modeled mathematically. The theory provides algorithms for the automatic synthesis of event disabling supervisors from their specifications. This thesis extends the basic supervisory control framework to make it more suitable for the real-time control of manufacturing systems.

A theoretical extension is the explicit introduction of real-time into the basic model. Most previous research focused on the ordering of events and abstracted their occurrence times away. In manufacturing systems, processing must typically be achieved within certain time windows if it is to be acceptable. The thesis extends the results of the basic theory to a timed supervisory control theory. It is shown that the timed synthesis problem can be solved in time polynomial in the number of system states, but exponential in the timing information.

Another relevant theoretical contribution is the introduction of an input-output semantics instead of the disabling semantics. The input-output controller synthesis problems for both an untimed and a timed plant are reduced to forms of the basic supervisor synthesis problem.

An implementation of the untimed synthesis algorithm, to which all considered synthesis problems can be reduced, is proposed. It is based on a data-structure known as Binary Decision Diagram (BDD). This compact symbolic representation method avoids the explicit enumeration of the entire discrete state-space. Its efficiency is demonstrated by a case-study of considerable size.

We also propose a general-purpose discrete event scheduler architecture for the sequential control of manufacturing systems. The scheduler is composed of a disabling supervisor, and of an input-output controller. Both devices enforce different types of specifications.

This thesis was motivated and strongly influenced by a semiconductor manufacturing multitasking control environment developed at the Stanford Center for Integrated Systems. Certain aspects discussed in this thesis have been implemented and tested for this environment.

V. Balakrishnan: Global Optimization in Control System Analysis and Design

Abstract: Many problems in control system analysis and design can be posed in a setting where a linear system is affected by unspecified parameters that lie between given upper and lower bounds. Except for a few special cases, the computation of many quantities of interest for such systems can be performed only through an exhaustive search in parameter space (which is a rectangle in our case).

Branch and bound algorithms provide one way of implementing this search for the global optimum in a systematic manner. These algorithms rely on easily computable upper and lower bounds for the global optimum over any parameter rectangle. First, upper and lower bounds are computed over the original parameter rectangle. These bounds are further refined by breaking up the parameter rectangle into sub-rectangles ("branching") to derive bounds for the global optimum over the original rectangle ("bounding"). The branching is done based on some heuristic rules. As they progress, branch and bound algorithms maintain upper and lower bounds for the global optimum; thus termination at any time yields guaranteed bounds for the optimum.

In this thesis, we describe a simple branch and bound algorithm for global optimization and prove its convergence. We then apply it towards the computation of several quantities (worst- and best-case state decay rate and worst- and best-case norms) that arise in the analysis and design of parameter-dependent linear systems.

List of Presentations

October 1, 1991 – September 30, 1992

- Young Man Cho,
Model Identification in Rapid Thermal Processing,
North Carolina State Univ., Raleigh, NC, April 30, 1992.
- Young Man Cho,
Model Identification in Rapid Thermal Processing,
Rockwell International Science Center, Thousand Oaks, CA, July 7, 1992.
- Young Man Cho,
Fast Identification of State Space Models via Exploitation of Displacement
Structure Univ. of California at Santa Barbara, Santa Barbara, CA, July 8,
1992.
- Paul J. Gyugyi,
A Real Time Control System for Semiconductor Equipment,
Digital, Cupertino, CA, August 13, 1992.
- G. Hoffmann,
Discrete Event Systems and Manufacturing, Systems Control Group, (Prof.
Wonham) University of Toronto, October 1991.
- G. Hoffmann,
Real-Time Discrete Event Systems,
Control Group, Dept. Of Electrical and Computer Engrg., (Prof. Varayia),
University of California at Berkeley, October 1992.
- T. Kailath,
Signal Processing and Control in Semiconductor Manufacturing,
Fourth Annual Rockwell Int'l. Control/Signal Processing Conference, Anaheim,
CA, January 1992.
- T. Kailath,
Control and Signal Processing in Semiconductor Fabrication,
Systems Research Center Colloquim, University of Maryland, February 1992
- T. Kailath,
Signal Processing and Control in Semiconductor Fabrication,
Automatic Control Laboratory, ETH-Zentrum, Zurich, Switzerland, May 1992

- T. Kailath,
Control and Signal Processing in Semiconductor Fabrication,
Industrial Control Centre, University of Strathclyde, Glasgow, Scotland, May
1992
- T. Kailath,
Signal Processing Applications in Semiconductor Processing,
National University of Singapore, July 1992
- T. Kailath,
Sensor Array Processing Techniques for Edge Detection,
Indian Institute of Science, Bangalore, India, July 1992
- T. Kailath,
Signal Processing and Control in Semiconductor Fabrication,
Hong Kong University of Science and Technology, August 1992
- T. Kailath,
Signal Processing and Control in Semiconductor Fabrication,
Engineering Systems Colloquium, University of California, Berkeley, November
1992
- C. Schaper,
Multivariable Control of RTP,
SEMATECH Expert Panel on RTP, Dallas, TX, 1991.
- C. Schaper,
Control and Singal Processing in Semiconductor Manufacturing,
SEMATECH Advanced Equipment Control Workshop, Phoenix, AZ, 1992.
- C. Schaper,
Multivariable Control of RTP,
SEMATECH Advanced Equipment Control Workshop, Dallas, TX, 1992.
- C. Schaper,
Multivariable Control of RTP,
SEMATECH, Austin, TX, 1992

Presentations without Proceedings October 1, 1991 – September 30, 1992

- C.-Y. Chang, C. Schaper and T. Kailath,
Computer-Aided Optimal Design of Phase-Shifting Masks,
7th annual SRC/DARPA CIM-IC workshop (Computer-Integrated Manufacturing of Integrated Circuits), August 5-6, 1992, Stanford University.
- Paul Gyugyi, Paul Dankoski, Gene Franklin,
Application of Control Theory to the Generation and Improvement of Wafer Recipes.
7th annual SRC/DARPA CIM-IC workshop (Computer-Integrated Manufacturing of Integrated Circuits), August 5-6, 1992, Stanford University.
- Gerard Hoffmann, and Gene Franklin,
Synthesis of Supervisory Controllers for IC-CIM,
7th annual SRC/DARPA CIM-IC workshop (Computer-Integrated Manufacturing of Integrated Circuits), August 5-6, 1992, Stanford University.
- G. Hoffmann and H. Wong-Toi,
Control of infinite Behavior of real-time discrete event systems,
Workshop on Discrete Event Systems, Prague, 1992.
- Babak Khalaj, Hamid Aghajan, Thomas Kailath,
Automatic Inspection Of Patterned Wafers
7th annual SRC/DARPA CIM-IC workshop (Computer-Integrated Manufacturing of Integrated Circuits), August 5-6, 1992, Stanford University.
- K. Saraswat, P. Apte, L. Booth, P. Gyugyi, C. Schaper, E. Wood, and S. Wood,
Demonstration of Flexible IC Mfg. Through Multiprocessing,
7th annual SRC/DARPA CIM-IC workshop (Computer-Integrated Manufacturing of Integrated Circuits), August 5-6, 1992, Stanford University.
- C. Schaper, et al.,
Multivariable Control of RTP,
7th annual SRC/DARPA CIM-IC workshop (Computer-Integrated Manufacturing of Integrated Circuits), August 5-6, 1992, Stanford University.
- Yao-T Wang, C. Schaper and T. Kailath,
Pattern Recognition of Trench Width using a Confocal Microscope,
7th annual SRC/DARPA CIM-IC workshop (Computer-Integrated Manufacturing of Integrated Circuits), August 5-6, 1992, Stanford University.